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PROGRESS REPORT

[illegible] INFLUENCING THE FATIGUE LIFE OF AN HY-80 [illegible] STEEL FULLY QUENCHED AND TEMPERED TO VARIOUS STRENGTH LEVELS

by

[illegible] and M. L. Salive

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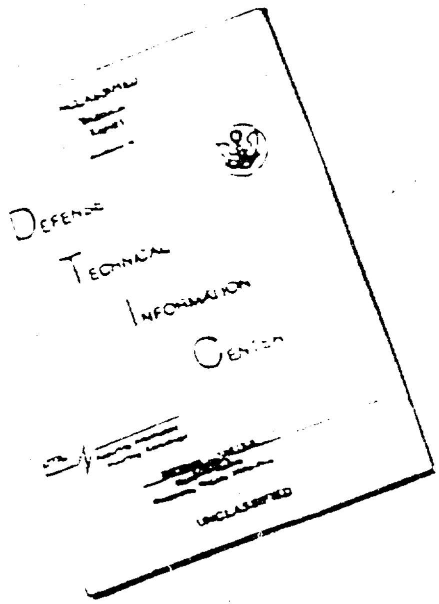

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PROGRESS REPORT

FACTORS INFLUENCING THE FATIGUE LIFE OF AN HY-80 COMPOSITION STEEL FULLY QUENCHED AND TEMPERED TO VARIOUS STRENGTH LEVELS

by

A. R. Willner and M. L. Salive

June 1964

Report 1807
S-F013 03 02
Task 2018

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ABSTRACT

This progress report evaluates the effects of strength level, Charpy V-notch energy, prestraining, prestraining and stress relieving, and austenitizing temperature on the fatigue life of a fully quenched HY-80 steel composition. The fatigue data developed herein indicate that the designer would have to be cautious when going to higher strength steel when using a safety factor which is considered satisfactory for lower strength steels, i.e., if higher strength steels are to be used, larger safety factors are necessary to obtain a comparable fatigue life. The limited data presented on experimental HY-150 steels indicate that caution will have to be exercised in evaluating large-specimen fatigue data.

INTRODUCTION

The data given in this report were prepared for presentation at a Low-Cycle Fatigue Colloquium held at the Marine Engineering Laboratory on 9 and 10 December 1963.

The data and discussion presented are only a fraction of the information compiled and analyzed by the Model Basin on the influence of metallurgical factors on the fatigue life of an HY-80 steel. A series of reports is being prepared to cover the full scope of this work. Accordingly, this present paper is intended as a progress report.

This study was performed under Bureau of Ships assignment S-F013 03 02, Task 2018.*

The metallurgical evaluation of HY-80 steels taken from models fatigue tested to destruction permit only a gross metallurgical description. Very little data were available to aid in interpreting the influence on fatigue life resulting from nonmartensitic products, prior austenitic grain size, strength level, and prestraining; in other words, the magnitude of

*Bureau of Ships letter C-NP/S, serial 320-060 of Oct 1961.

the individual effects of these metallurgical factors on fatigue life could not be assessed on the basis of routine laboratory examinations.

Accordingly, a limited program was undertaken to systematically investigate the effects of various metallurgical factors on the fatigue life of an HY-80 steel; see Figure 1. Briefly, the fatigue study entails the following:

1. Four yield strength levels (85, 105, 120, and 150 ksi).
2. Two grain sizes (ASTM 9 and ASTM 4) at the 105-ksi yield strength level.
3. Three microstructures (martensite, bainite, and ferrite) at the 85-, 105-, and 120-ksi yield-strength levels.
4. Evaluation of fatigue specimens:
   a. In the as-heat-treated condition.
   b. After prestraining 2 percent in tension or compression.
   c. Stress relieving after prestraining.

Each group of fatigue specimens was tested at a nominal 80, 95, 105, and 115 percent of its yield strength.

MATERIAL

Figure 2 depicts the upper and lower bounds of maximum transverse Charpy V-notch energy for commercially produced HY-80 compositions heat treated to various strength levels. The HY-80 steel selected for this investigation (DTMB plate E103) falls at the lower bound. It is interesting to note that HY-80 steel HC, which falls at the upper bound, has a chemistry similar to that of DTMB plate E103 which falls on the lower notch toughness bound.

The effects of varying the microstructure by isothermal treatments on the notch-toughness properties for different yield strengths of the HY-80 steel selected for this investigation are shown in Figure 3. The tempered martensitic structure indicated by the solid line had generally the best notch-toughness properties. The effects of various percentages of nonmartensitic products will be discussed in subsequent reports. Specimens austenitized at 2000 F (not shown on this curve) had NDT temperatures about 100 F higher for any given strength level. However, the maximum Charpy V-notch energy levels were the same. Correlations between Charpy V-notch maximum energy and fatigue life will be presented in the test results.

The stress-strain curves obtained after heat treatment are depicted in Figure 4. This figure shows the effects of various tempering temperatures and microstructures on the yielding characteristics of the HY-80 steel used in this investigation. Except for the specimens heat treated to the 162-ksi yield strength, all stress-strain curves demonstrated plateau, or semi-plateau yielding characteristics. Load-strain curves extended to a total of 2 percent indicated that the yield-point elongation did not go significantly above the stress level indicated at the termination point of each stress-strain curve shown in Figure 4.

A Bauschinger effect was introduced by the prestraining. Specimens which were stress relieved after prestraining showed that the as-heat-treated yield strengths were not exceeded when tested either in tension or compression. In fact, the character of the prestrained and stress-relieved stress-strain curve was similar to that of the as-heat-treated material, indicating that stress relieving had not introduced strain aging, and had eliminated Bauschinger effect.

An investigation of over one thousand commercially produced HY-80 steel plates showed that the majority of the plates had upper and lower yield points, or plateau-yielding characteristics similar to those shown in Figure 4. The stress-strain curves that exhibit upper and lower yield points, or plateau yielding, are considered discontinuous since both curves have an extended area, usually around 2 percent, where the strain increases without increases in stress. This increase in deformation without additional stress is called the yield-point elongation. Therefore, the stress-strain curves shown in Figure 4 are considered typical of those found for commercially produced HY-80 steels.

Figure 5 shows the relationship between yield strength and tensile strength for the three microstructures investigated; to summarize:

1. For 100 percent martensite:
   a. Up to 110-ksi yield strength, the yield strength increases more rapidly than the ultimate tensile strength.

   b. From 110- to 140-ksi yield strength, the yield strength and ultimate strength increase proportionately.
   c. From 140- to 165-ksi yield strength, the ultimate tensile strength increases at a greater rate than the yield strength.
   d. A reversal in yield strength occurs at ultimate tensile strengths exceeding 180 ksi.
2. For 50 percent bainite and 50 percent martensite:
   a. The ratio of yield strength to ultimate tensile strength is lower for the structure containing bainite than for the 100 percent martensitic structure for all yield strengths in excess of 80 ksi.
   b. Yield strengths increase at a greater rate than the ultimate tensile strength up to a yield strength of 120 ksi.
   c. After 120-ksi yield strength, the ultimate tensile strength increases at a greater rate than the yield strength.
3. For 25 percent ferrite and 75 percent martensite:
   a. At 80-ksi yield strength and above, the ratio of yield strength to ultimate tensile strength is lowest for structures containing ferrite.
   b. Up to 80-ksi yield strength, the yield strength increases more rapidly than the ultimate tensile strength.
   c. At a yield strength greater than 80 ksi, both yield strength and tensile strength increase at about the same rate.

From Figure 5, it can generally be stated that from 80- to 90-ksi yield strength, the ratios of yield strength to ultimate tensile strength are the same, 0.80 to 0.85. The significance of Figure 5 for evaluating fatigue characteristics based on submersible design concepts will be covered in the discussion.

SPECIMENS AND TEST PROCEDURES

Standard R. R. Moore simple beam fatigue specimens were used in this study, as shown in Figure 6. All specimens were mechanically polished so that the final polishing marks were parallel to the major longitudinal axis of the specimen. Five specimens were used to define the fatigue life of each of the stress levels investigated.

The required loads were applied by use of a hydraulic jack arrangement; i.e., the weights were slowly lowered on the specimen as it was rotating. After full application of load, the cycles and time to failure were noted. All specimens were tested at a nominal 2000 rpm. At failure, the specimens showed none of the temper colors which are indicative of overheating; however, there were indications that some of the specimens warmed up just prior to failure.

Immediately after final polishing and during fatigue testing, the specimens were coated with dodecyl alcohol to avoid variables introduced by environmental conditions such as high humidity.

TEST RESULTS

Since this is a progress report, the raw data, the least square equations, and standard deviations will be tabulated for all test conditions and reported as a supplement to the final report.

APPLIED STRESS VERSUS LOG NUMBER OF CYCLES TO FAILURE

Presented in Figure 7 are curves showing the standard applied stress versus log number of cycles to failure obtained from four different yield-strength levels of fully tempered martensite from 89 to 162 ksi. The static tensile proportional limits and yield strengths are superimposed on these curves. The following observations can be made from Figure 7:

1. As expected, the higher the yield-strength level, the longer the fatigue life for the applied stress levels investigated.
2. Regardless of strength, when the applied load equals the static yield strength, the fatigue life falls between 5000 to 20,000 cycles; therefore, any HY-80 structure alternately cycled at its yield strength can be expected to have a fatigue life of less than 20,000 cycles.
3. When loaded to the proportional limit, an infinite life is obtained only for the specimens heat treated to 89-ksi yield strength. Since the fatigue specimens used in this study can be considered ideal, an HY-80 structure subjected to fatigue can be expected to have a finite life rather than an infinite life period when stressed to its static proportional limit.

EFFECTS OF RATIO OF APPLIED STRESS TO MECHANICAL PROPERTIES ON FATIGUE LIFE

The Navy procures HY-80 steel under military specification MIL-S-16216G. One of the main mechanical-property requirements is that HY-80 steel normally used in structures shall have a yield strength ranging from 80 to 95 ksi. No minimum is required for ultimate tensile strength. Therefore it can be deduced from the mechanical properties specified in MIL-S-16216G that the structural designer uses as safety factors, various ratios of of structural loads to yield strength rather than to ultimate tensile strength. If this is the case, then fatigue life for a given structure has to be evaluated as a function of the ratio of applied stress to yield strength.

When the fatigue data given in Figure 7 are replotted to show the ratio of applied stress to yield strength (Figure 8), it can be clearly seen that for a given ratio, the lower strength fatigue specimens had the longer life.

If the designer wishes to use some ratio of the elastic portion of the stress-strain curve as a basis for determining his safety factor, then it can be clearly seen (Figure 9) that the highest strength material has the lowest fatigue life as determined by the ratio of applied stress to tensile proportional limit versus log number cycles to failure.

It is customary in engineering tests to compare fatigue life to the ratio of applied stress to ultimate tensile strength for various steels or for the same steels having various strengths. Figure 10 is such a plot for HY-80 steel heat treated to various strength levels. This figure shows that there is no significant difference in fatigue life when these steels are compared on the basis of the ratio of applied stress to ultimate tensile strength.

Figure 11 clearly depicts the effects of tensile yield strength on the fatigue life of ideal specimens for given ratios of applied stress to tensile yield strength. Standard deviation depicted in this figure shows that the curves obtained for each given ratio do not overlap and that the fatigue data are distinctive for each tensile yield-strength level.

EFFECTS OF PRESTRAINING AND STRESS RELIEVING ON FATIGUE LIFE

The effects of prestraining in tension, compression, and stress relieving after prestraining are shown in Figure 12, where the effects of tensile yield-strength level versus fatigue life are plotted for various ratios of applied stress to tensile yield strength. From Figure 13, which is a composite of the effects of various conditions of prestraining and stress relieving on the HY-80 steel heat treated to 80,000-psi yield strength, it can be seen that 2 percent prestraining in tension, or compression, or after stress relieving had very little effect on the fatigue life for ratios of applied stress to tensile yield strength above 0.85. It is interesting to note that the as-heat-treated specimens and those prestrained in tension and stress relieved had infinite fatigue life for ratios below 0.80; the other specimens at this ratio had finite fatigue lives.

EFFECTS OF AUSTENITIZING TEMPERATURE ON FATIGUE LIFE

The effects of austenitizing temperature were negligible on the fatigue life of HY-80 steel heat treated to 111,000-psi tensile yield strength, as shown in Figure 14.

EFFECTS OF MAXIMUM CHARPY V-NOTCH ENERGY ON FATIGUE LIFE

Figure 3 shows that there was a decisive effect of tensile yield strength on transverse Charpy V-notch maximum energy absorbed and on NDT temperatures. The question then arises as to whether these notch-toughness properties can be related to fatigue life.

The effects of the transverse Charpy V-notch level on fatigue life are plotted in Figure 15. It is interesting to note that the inflection in the curves occurs around the 45-ft-lb level. At the 150,000-psi yield-strength level, the transverse Charpy V-notch energy level was around 27 ft-lb.

To determine whether the Charpy V-notch level could be used as a criterion, an experimental 7 1/2-percent nickel steel (HY-150) and an HP-150 steel (Charpy values of 62 and 94 ft-lb, respectively) were fatigue-tested.

Figure 16 compares fatigue life for 7 1/2-percent nickel steel (HY-150) and HP-150 to that of HY-80 (plate E103) heat treated to the same strength level and to the same HY-80 composition heat treated to 90-ksi yield strength. This figure is a plot of the ratio of applied stress to yield strength versus number of cycles to failure for these three materials. It is interesting to note that the HY-80 heat treated to 150,000-psi yield strength and the HP-150 and HY-150 had identical yield strength to tensile strength ratios of 0.90 whereas the 90,000-psi yield strength HY-80 had a ratio of 0.85.

The HY-80 composition heat treated to 150,000-psi yield strength had the lowest fatigue limit. HY-150 and HP-150 can be considered as having the same fatigue life.

Using ideal specimens, the 7 1/2-percent nickel (HY-150), the HP-150, and the HY-80 compositions heat treated to 90-ksi yield strength appeared to have similar fatigue lives when stressed to 100 percent of their respective yield strengths. However, when fatigue tested at 80 percent of their yield strengths, HY-150 and HP-150 had a finite fatigue life (100,000 cycles) whereas HY-80 at 90,000 psi could be considered to have an infinite fatigue life.

The fatigue life of fully quenched and tempered steels of a given HY-80 composition appears to be related to yield strength to tensile strength ratio, to Charpy V-notch properties, and to strength level. When steels of other compositions, such as HY-150 and HP-150, are heat treated to a 150,000-psi yield-strength level having the same yield strength to tensile strength ratio and having high Charpy V-notch levels (above 50 ft-lb), the fatigue life of these steels is somewhat greater than the HY-80 composition at this strength level. Therefore, it is indicated that maximum Charpy V-notch energy has a contributory effect; probably the effects of impact strength would be more pronounced for specimens with greater cross-sectional areas than the specimens used in this investigation.

DISCUSSION

As indicated earlier, HY-80 steels specified under MIL-S-16216G are procured to yield strength rather than tensile strength. Since this is the case, the yield strength rather than the ultimate tensile strength has to be used as the fatigue design criterion.

The fatigue data presented herein indicate that the higher the yield strength, the shorter the fatigue life for a given ratio of applied stress to yield strength.

The heat affected zone (HAZ) of HY-80 weldment can be expected to have variations in strength level. Superficially, on the basis of nominal stress and strength of the HAZ, it would appear that fatigue failure should not initiate in the HAZ since the higher strength zone would have a lower working stress ratio and thus a greater fatigue life. Discounting for the present the effects of residual stress and variations in microstructure, the effects of strain have to be considered. Since the high-strength areas in the HAZ can be considered to have a width which is incrementally small, and if the base material of the structure yields in operation due to the presence of design discontinuities, it can be expected that these incremental high-strength areas will also yield to the same extent as the base material. If such is the case, then an effective high ratio of applied stress to yield strength will be experienced in the HAZ. Therefore, as shown in Figure 8, it can be expected that the high strength areas in the HAZ can become a nucleus for fatigue cracks.

One cannot use higher strength steels to the same design ratios as lower strength steels and still expect to get the same fatigue life. For instance, entering the curves shown in Figure 8, at a given number of cycles, say 10^5, the curve designating 89-ksi yield strength shows an applied stress to yield strength ratio of approximately 0.92, and the curve for the 108-ksi yield strength has a ratio of 0.87. This indicates that for the same fatigue life, increasing the yield strength by 21 percent will only increase the allowable applied stress by 14 percent. Figure 8 also shows the fatigue life for HY-80 to be two orders of magnitude higher than the fatigue life of HY-80 steel heat treated to 160,000-psi yield strength at a ratio of applied stress to yield strength of 0.80. Figure 16 shows this same magnitude of difference when a 90,000-psi yield strength HY-80 is compared to the experimental HY-150 and HP-150 steels.

An argument may be made that if the designer would use ultimate strength rather than yield strength as his design criterion, that for a given ratio of applied stress to ultimate tensile strength, the higher strength steel will have the same fatigue life as the lower strength materials, as indicated in Figure 10. But this assumption is not valid when one considers a design for submersibles. Design of submersibles is based on yielding, whether it be at the 0.2-percent offset yield strength or at some other yielding criterion, e.g., the value of either the ratios of secant modulus to Young's modulus or tangent modulus to Young's modulus. Using these yielding criteria, the ultimate tensile strength will have to be modified for the criterion used in the design; i.e., assuming the yield strength-tensile strength ratio is 0.84, then the tensile strength is reduced by the 0.84 factor when calculating the static strength of the structure. Then the fatigue design can be considered either on the basis of applied stress to 84 percent of the ultimate tensile strength or on the basis of applied stress to yield strength.

There is an indication from Figure 16 that the fatigue life of a material having a high yield strength may be improved if the maximum Charpy V-notch values can be raised above 40 ft-lb.

Prestraining 2 percent in either tension or compression can be considered to have negligible effect on the fatigue life. The effects on fatigue life of greater percentages of prestraining or of embrittlement due to stress relieving were not evaluated in this investigation.

It is interesting to note that grain size had no effect on the fatigue life of an HY-80 composition heat treated to the nominal 100,000-psi yield-strength level.

The intent of this report and the series of reports to follow is to indicate the metallurgical factors which may influence the fatigue life of HY-80 composition. The individual metallurgical factors may or may not be cumulative in their effect on the design fatigue life. These individual and combined effects will be evaluated in subsequent reports.

CONCLUSIONS

Since this investigation was primarily concerned with the effects of individual metallurgical factors, ideal fully quenched and tempered fatigue specimens were used. The conclusions presented are based on these ideal specimens tested under controlled laboratory conditions:

1. The fatigue life for a given ratio of working stress to mechanical strength has to be based on the criterion used to design a structure; i.e., if some ratio of the proportional limit, yield strength, or ultimate tensile

strength is used for design purposes, the fatigue life should be evaluated on the basis of the design ratio used.

2. The major metallurgical factor in reducing the effective working stress to yield strength ratio is increasing yield strength.

3. Prestraining 2 percent in tension or compression and stress relieving after prestraining can be considered to have very little effect on the fatigue life.

4. Grain size has no effect on the fatigue life of HY-80 composition steel heat treated to a nominal 100,000-psi yield-strength level.

5. Use of newer and higher strength fully martensitic steel alloys, such as HY-150 and HP-150, requires more detailed fatigue studies than reported herein. However, this study does indicate that caution will have to be exercised in analyzing model and large-specimen fatigue data.

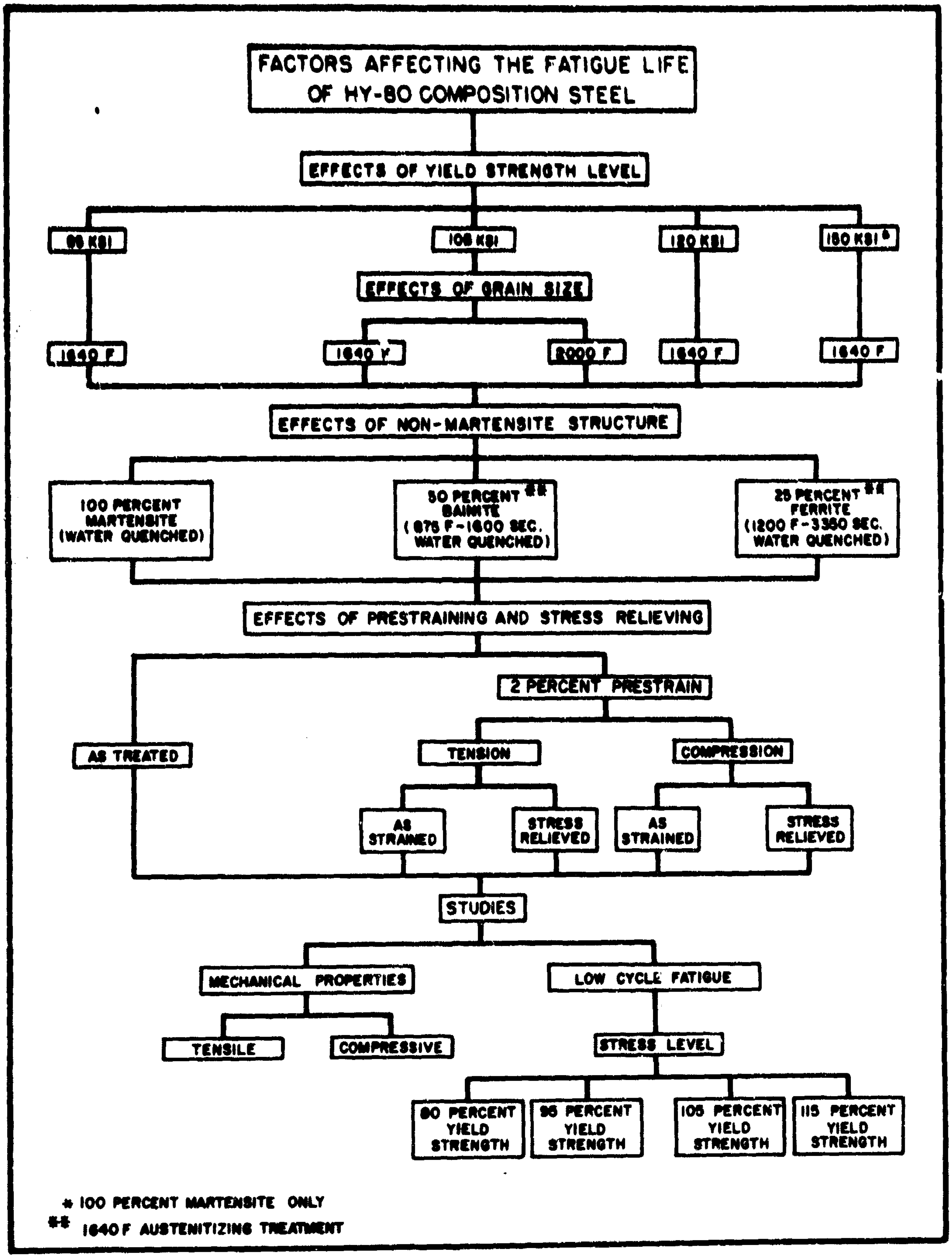

Figure 1 - Investigative Steps in the Fatigue Study of an HY-80 Composition

	CHEMICAL COMPOSITION IN PERCENT								
	C	Mn	P	S	Si	Ni	Cr	Mo	L_{SW-95}
HC	0.15	0.24	0.011	0.014	0.14	2.85	1.44	0.45	2.16
E 103	0.15	0.33	0.018	0.017	0.26	2.85	1.50	0.40	2.03

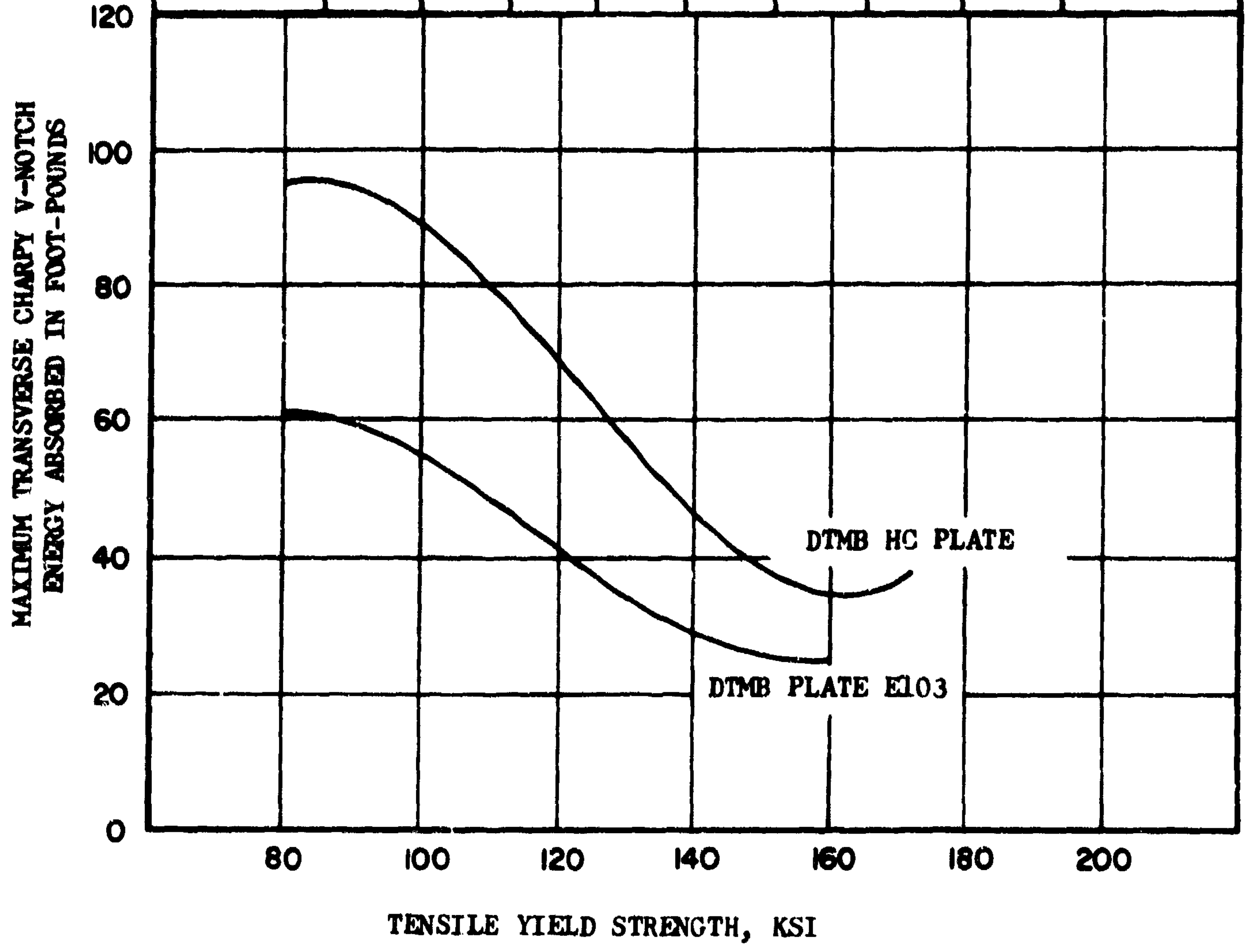

Figure 2 - Relationship between Tensile Yield Strength and Maximum Transverse Charpy V-Notch Energy for Various Fully Quenched and Tempered HY-80 Steels

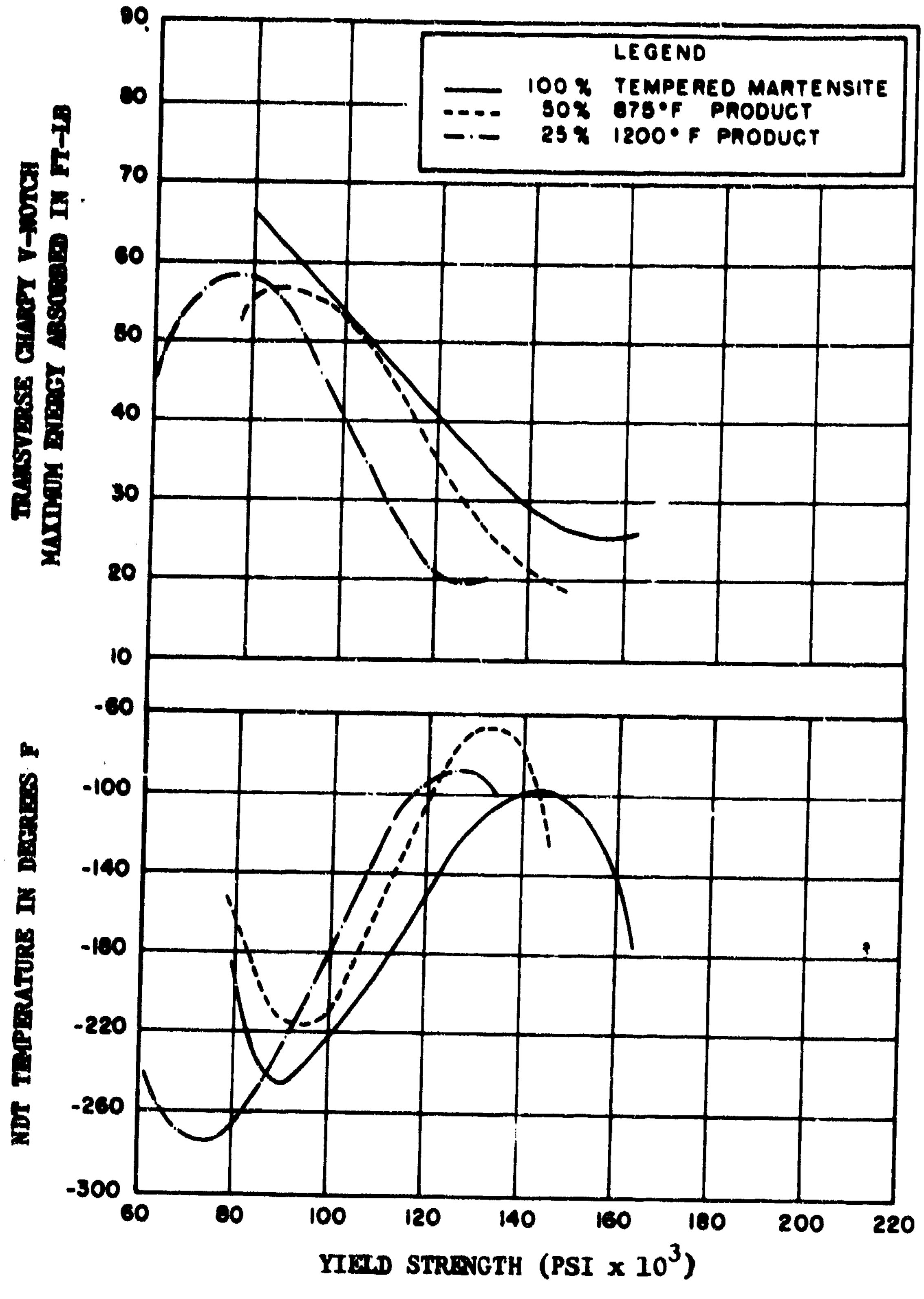

Figure 3 - Effects of Tensile Yield Strength on the Notch-Toughness Properties of an HY-80 Steel Heat Treated to Contain Various Microstructures

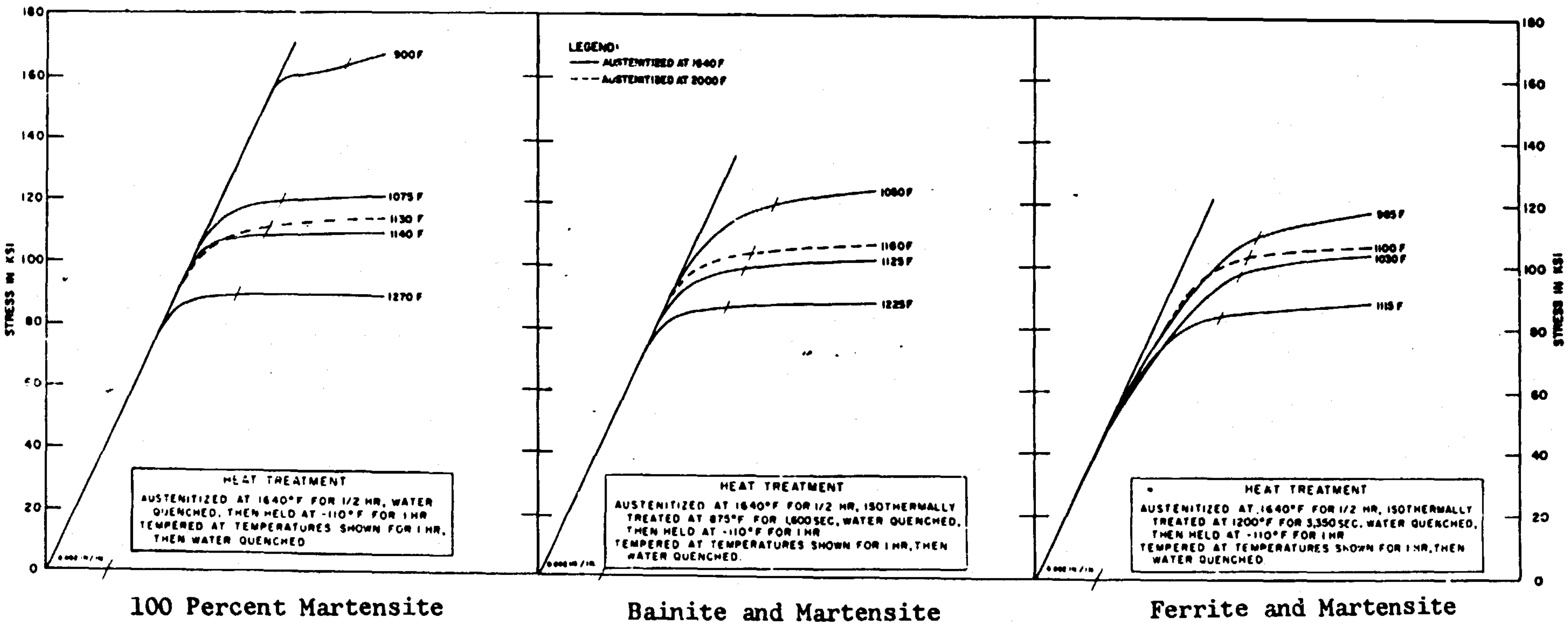

Figure 4 - Effects of Various Tempering Temperatures and Microstructures on the Yielding Characteristics of an HY-80 Composition

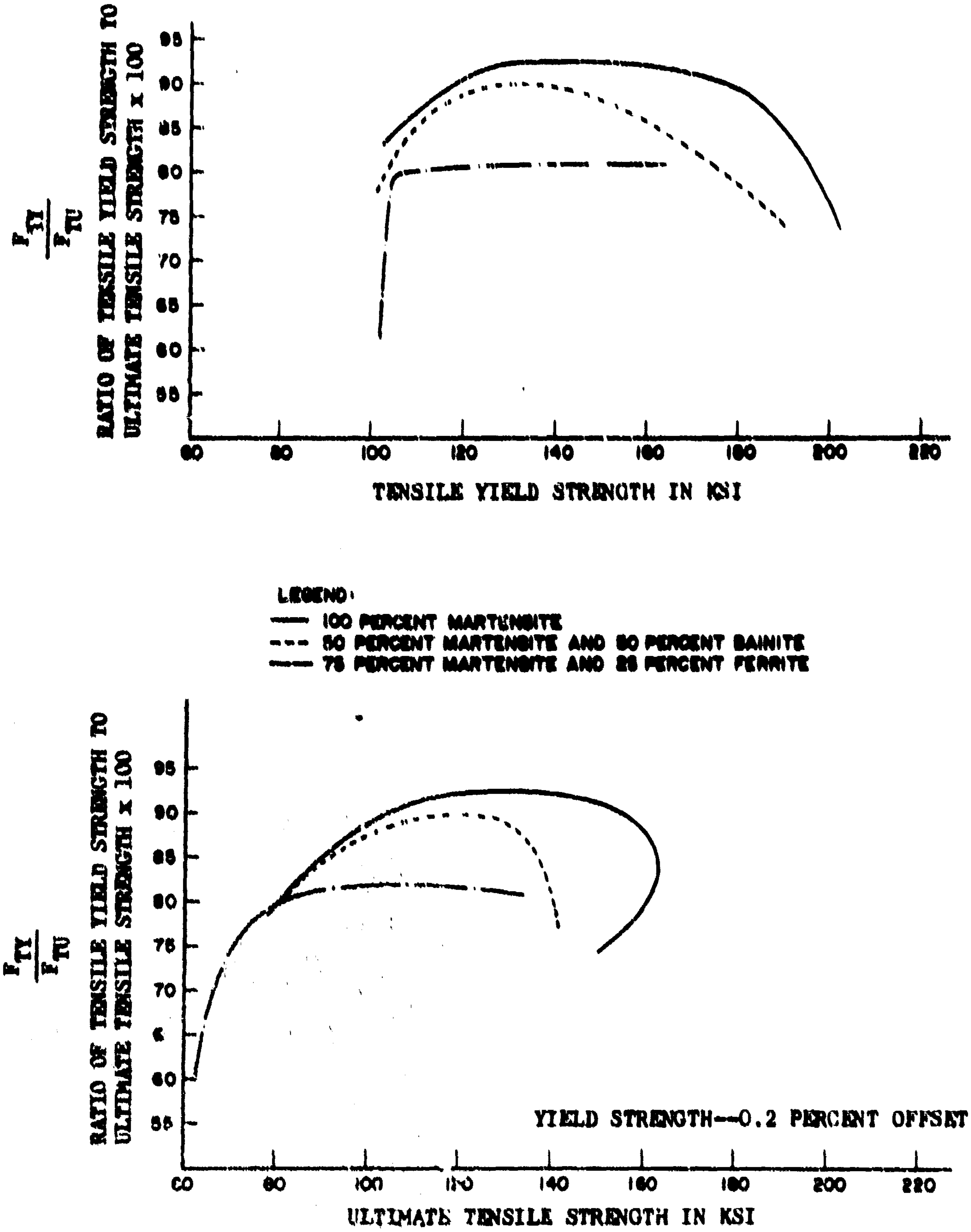

Figure 5 - Effects of Microstructure and Strength Level on the Ratio of Tensile Yield Strength to Ultimate Tensile Strength

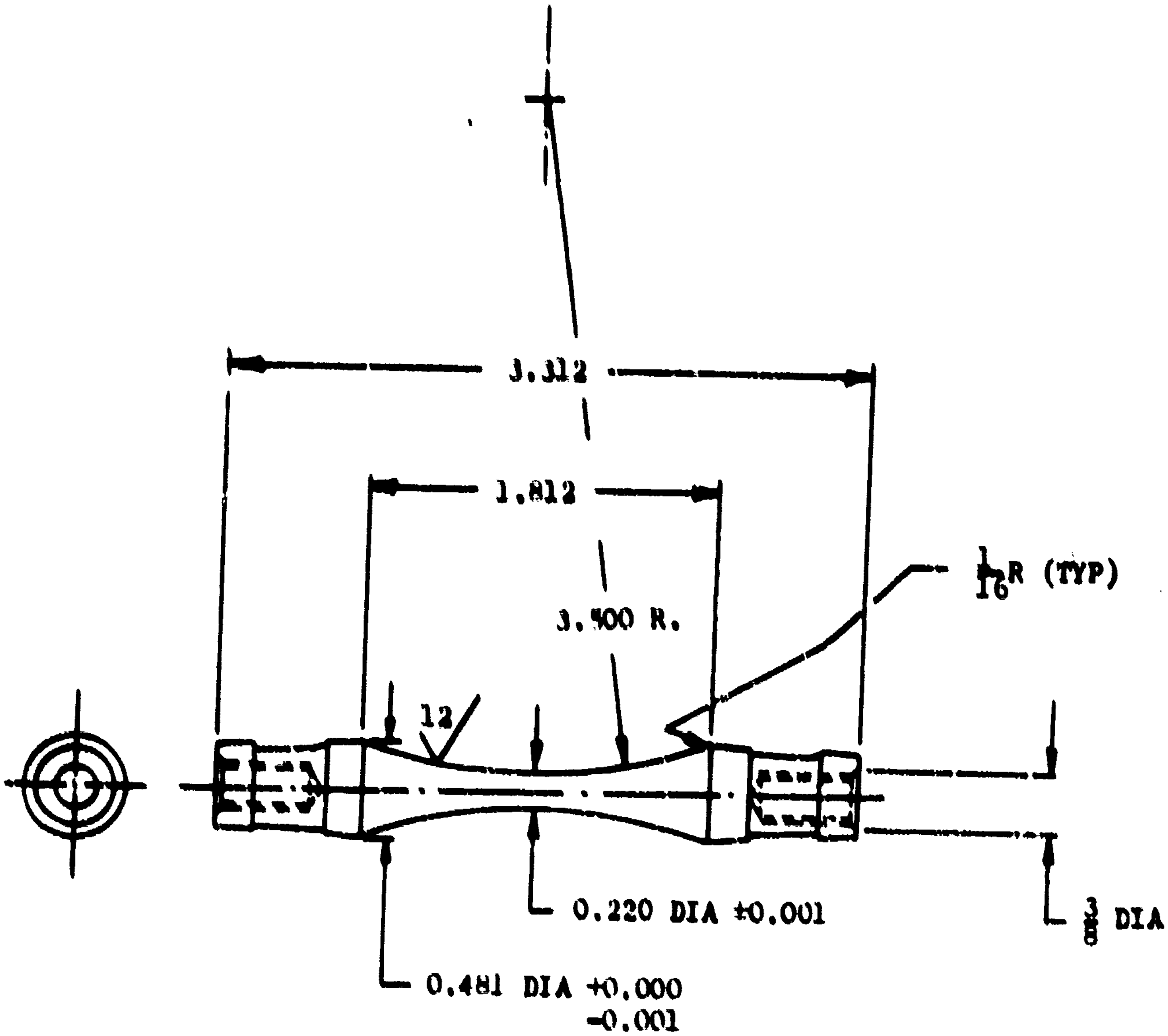

Figure 6 - Standard R. R. Moore Fatigue Test Specimen

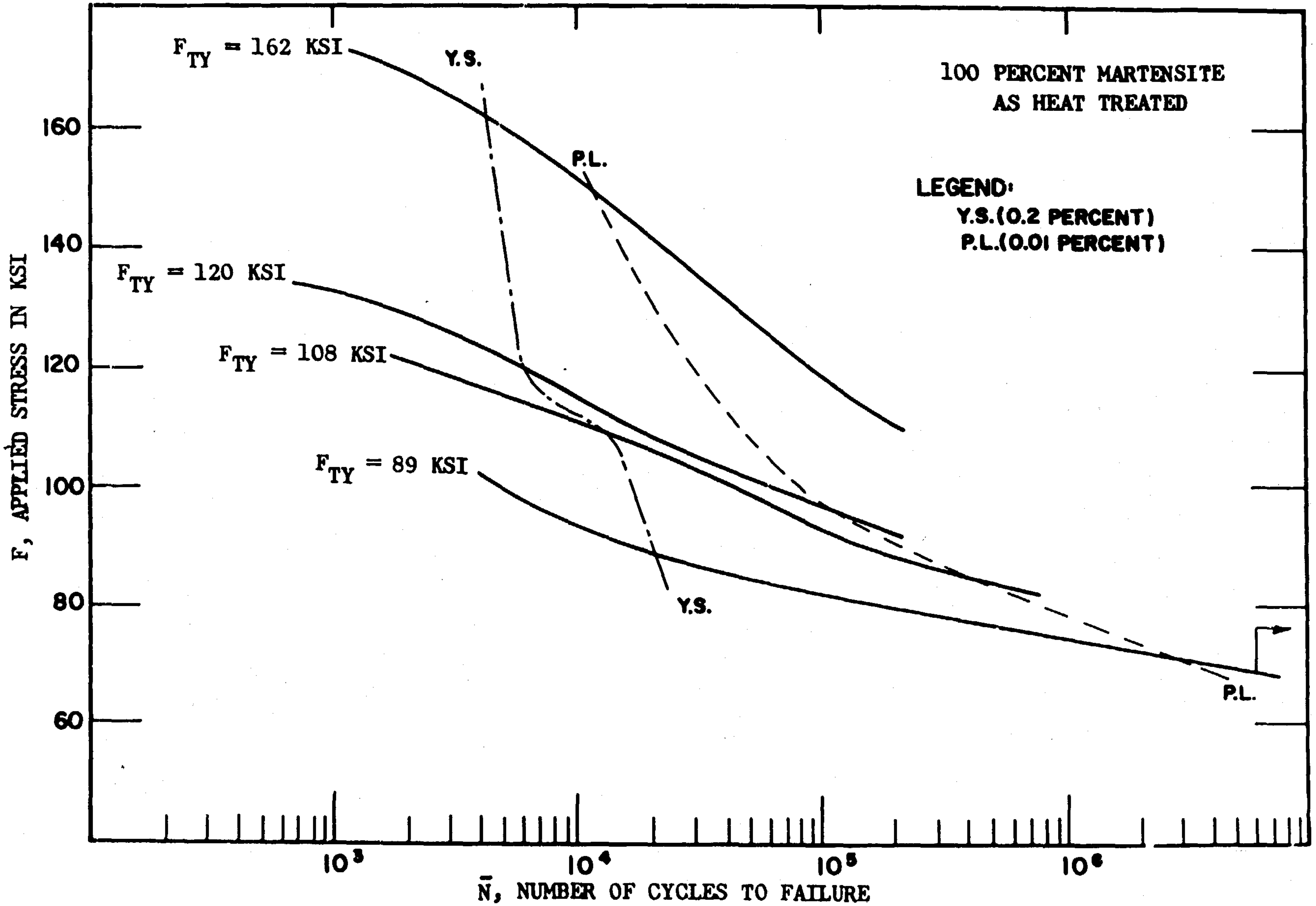

Figure 7 - Applied Stress versus Log Number of Cycles to Failure for an HY-80 Composition Heat Treated to Four Different Yield Strength Levels

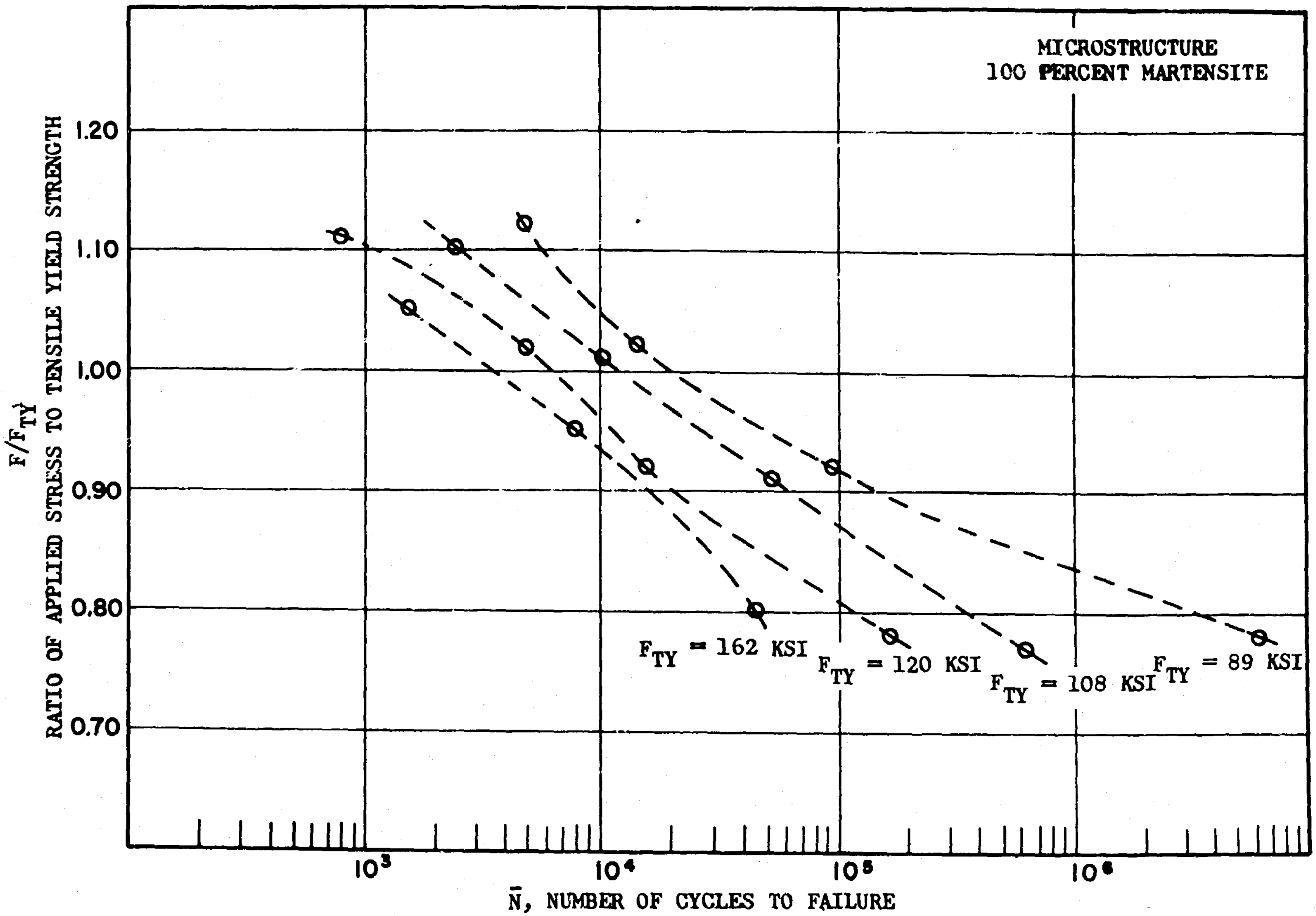

Figure 8 - Ratio of Applied Stress to Tensile Yield Strength versus Log Number of Cycles to Failure for a HY-80 Composition Heat Treated to Four Strength Levels

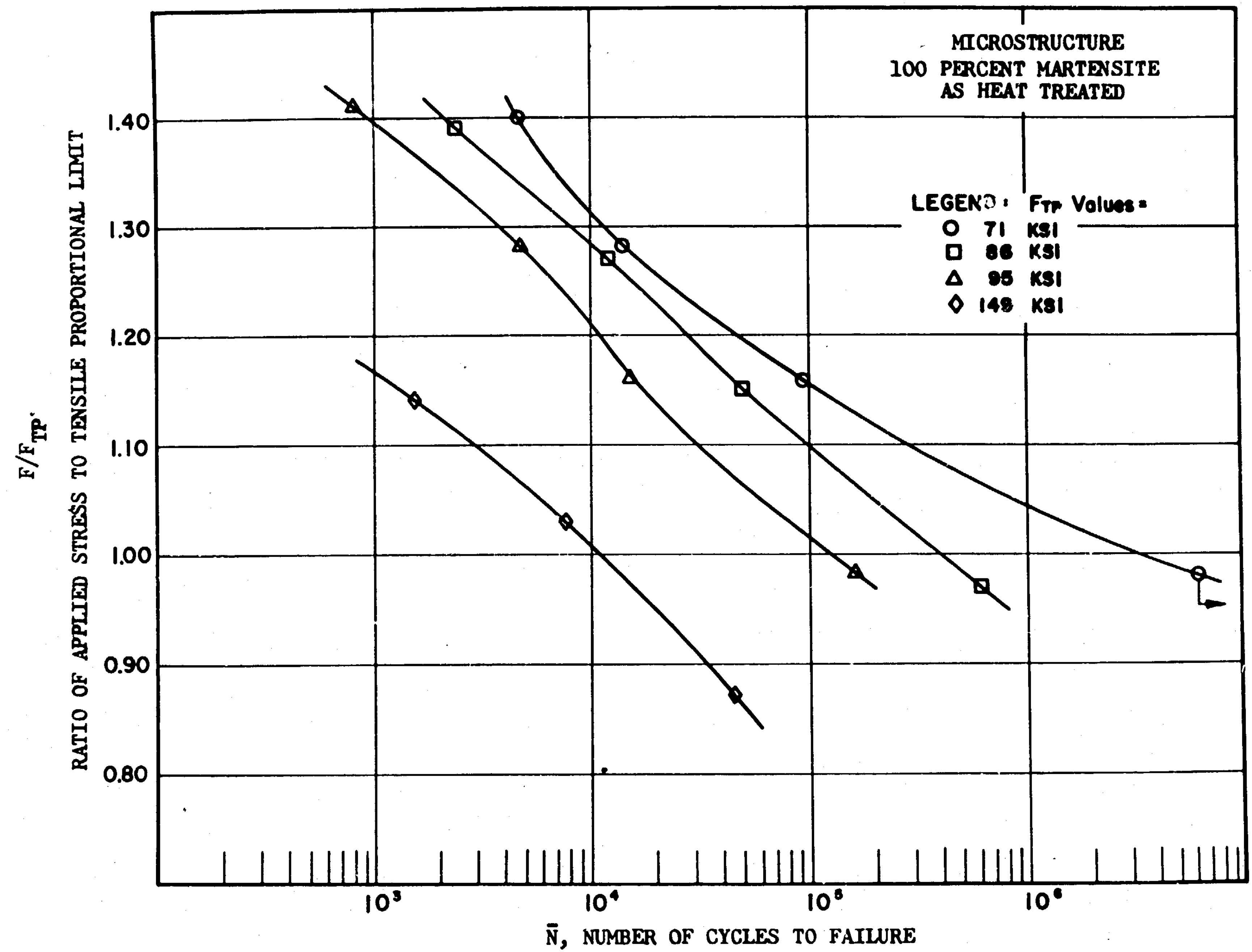

Figure 9 - Ratio of Applied Stress to Tensile Proportional Limit versus Log Number of Cycles to Failure for an HY-80 Composition Heat Treated to Four Strength Levels

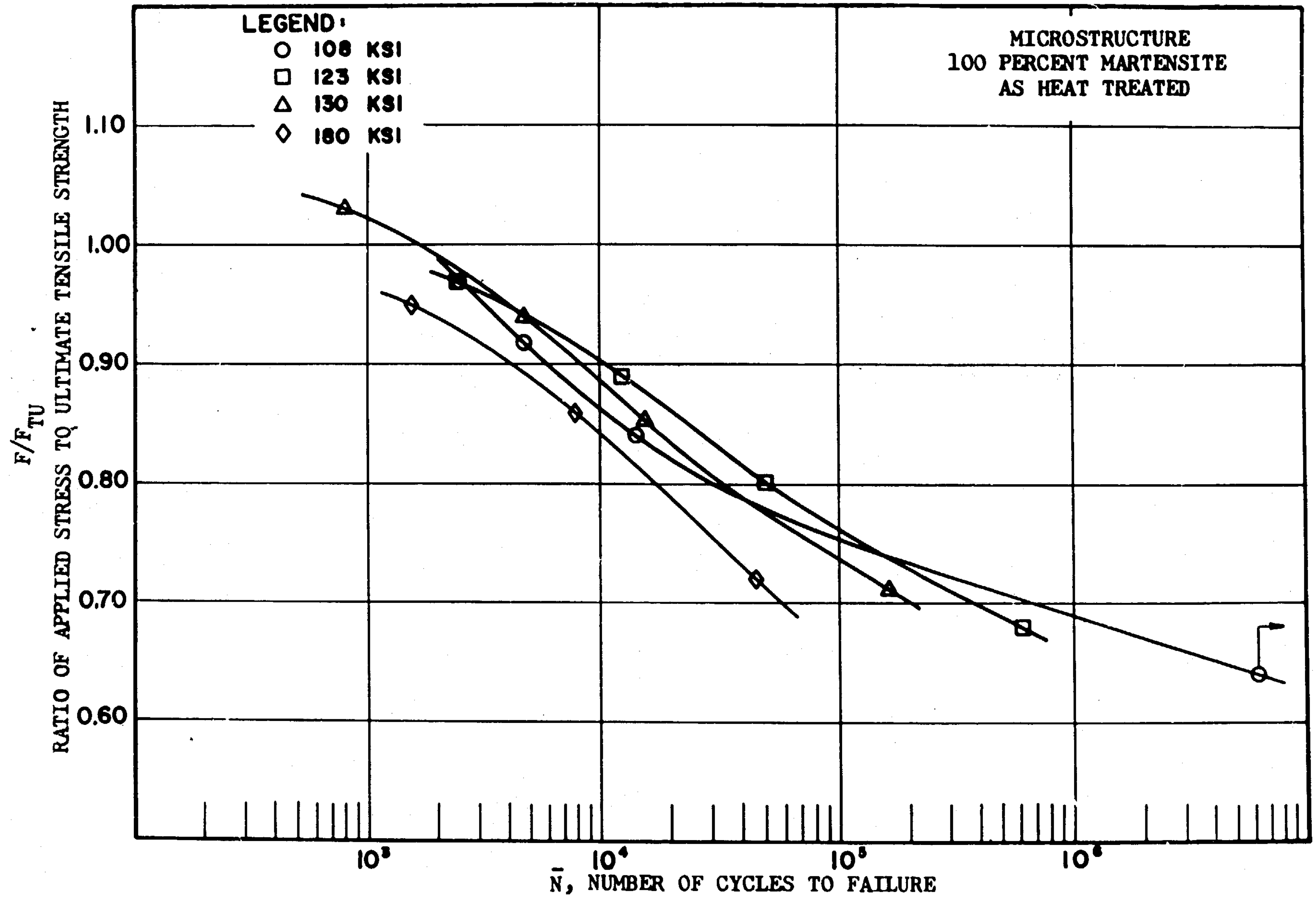

Figure 10 - Ratio of Applied Stress to Ultimate Tensile Strength versus Log Number of Cycles to Failure for an HY-80 Composition Heat Treated to Four Strength Levels

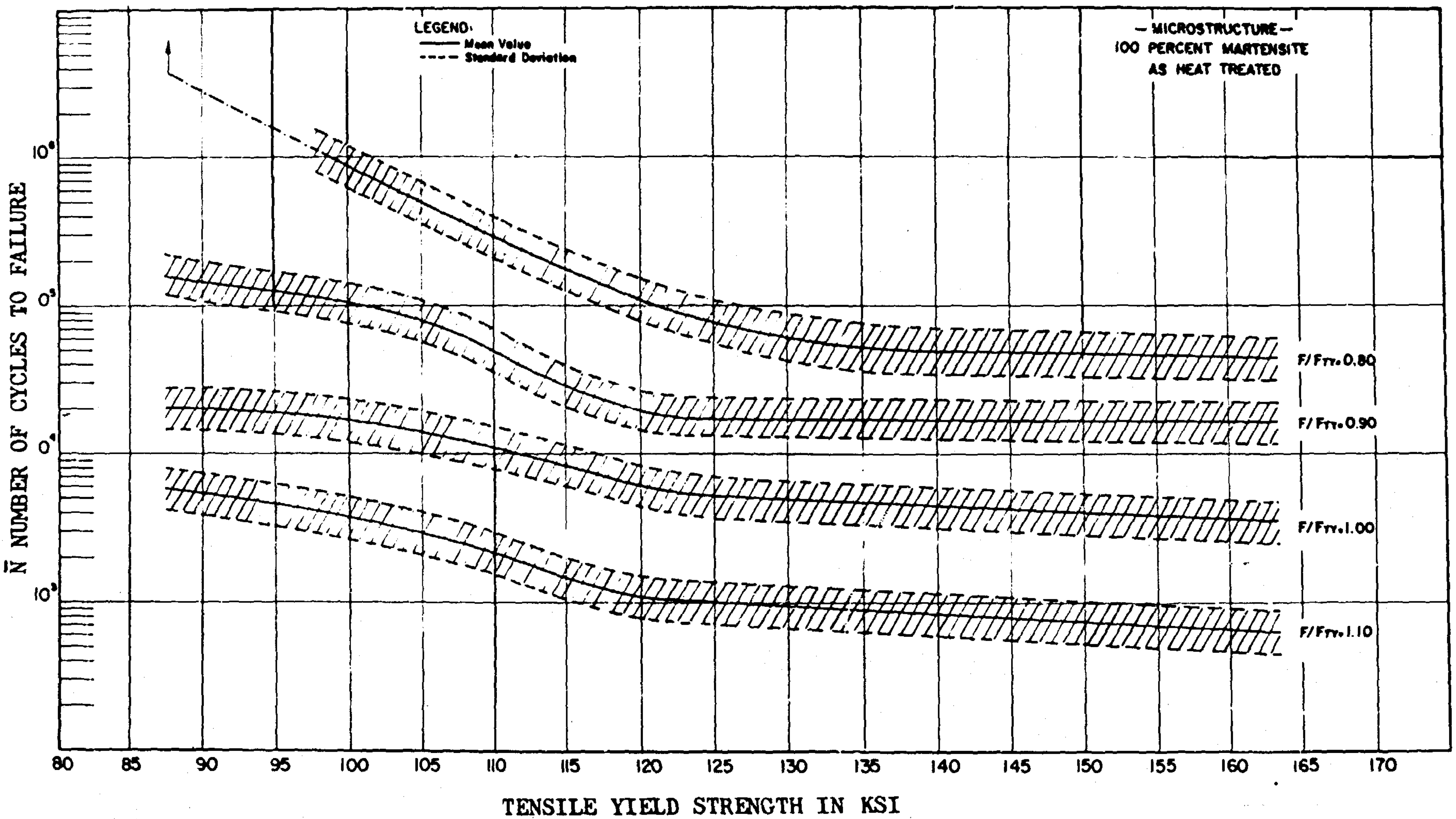

Figure 11 - Tensile Yield Strength versus Log Number of Cycles to Failure for an As-Heat-Treated HY-80 Composition at Four Ratios of Applied Stress to Tensile Yield Strength

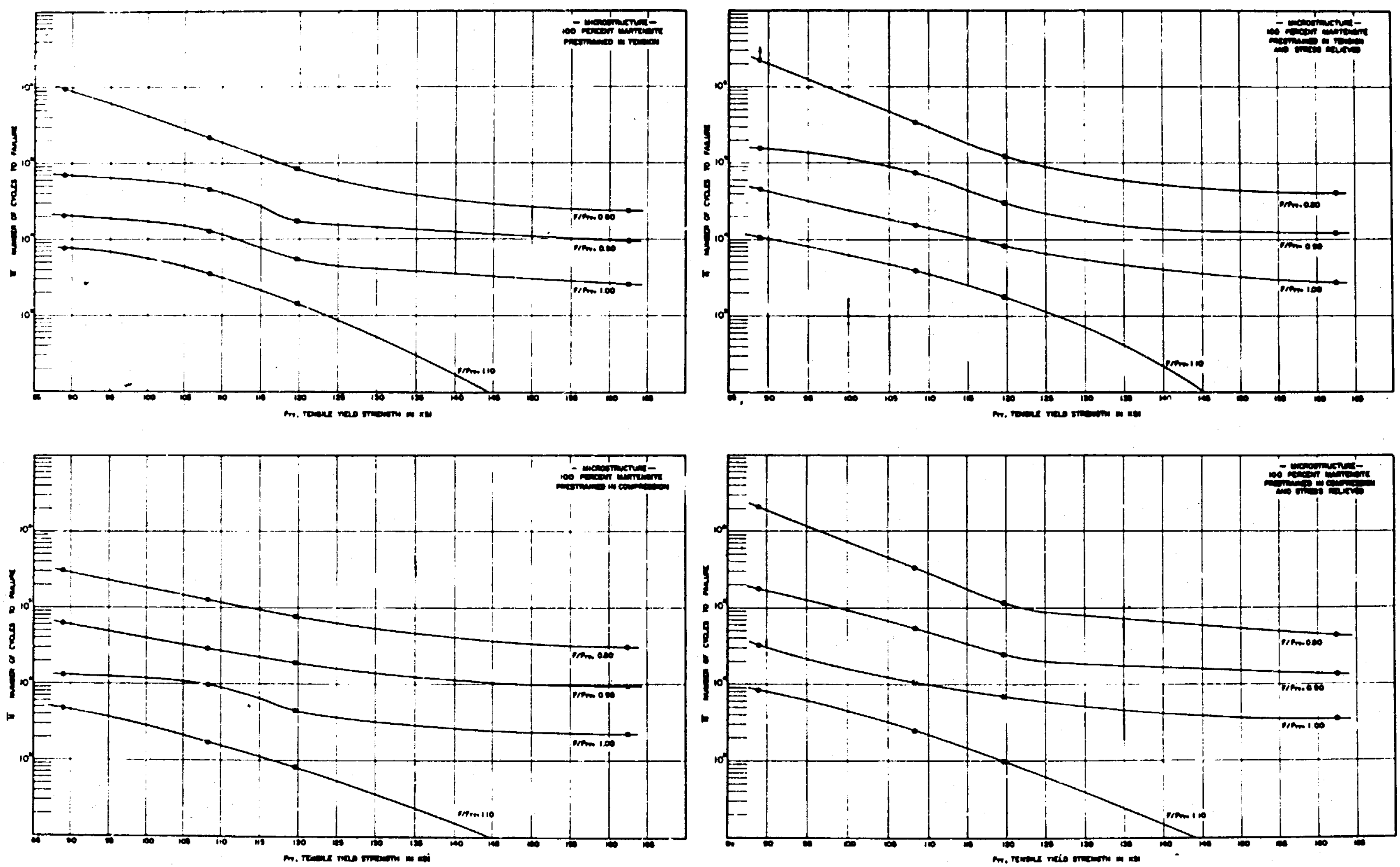

Figure 12 - Tensile Yield versus Log Number of Cycles to Failure for Prestrained, and Prestrained and Stress Relieved HY-80 Composition at Four Ratios of Applied Stress to Tensile Yield Strength

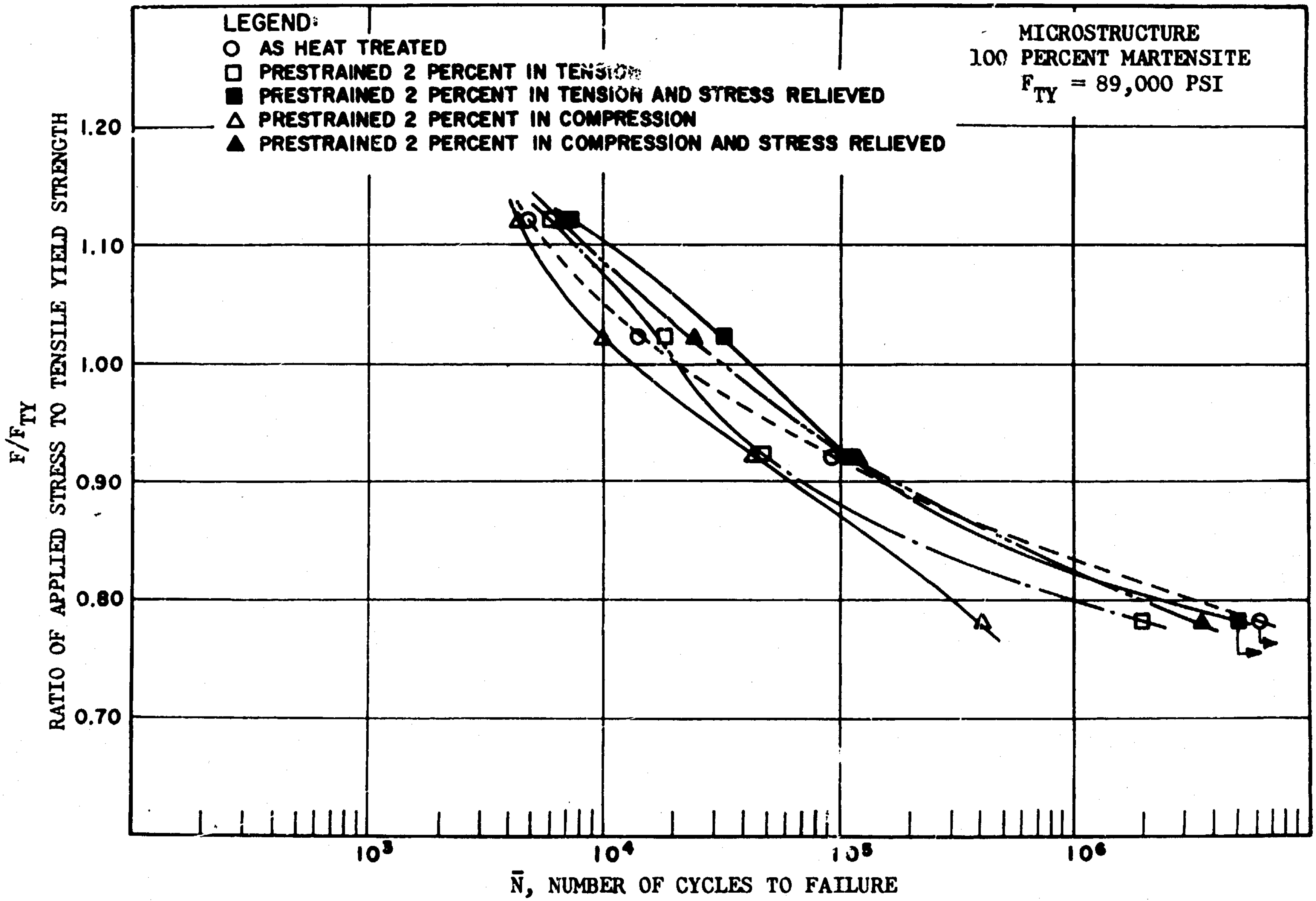

Figure 13 - Ratio of Applied Stress to Tensile Yield Strength versus Log Number of Cycles to Failure for an HY-80 Steel in the As-Heat-Treated, Prestrained, and Prestrained and Stress Relieved Condition

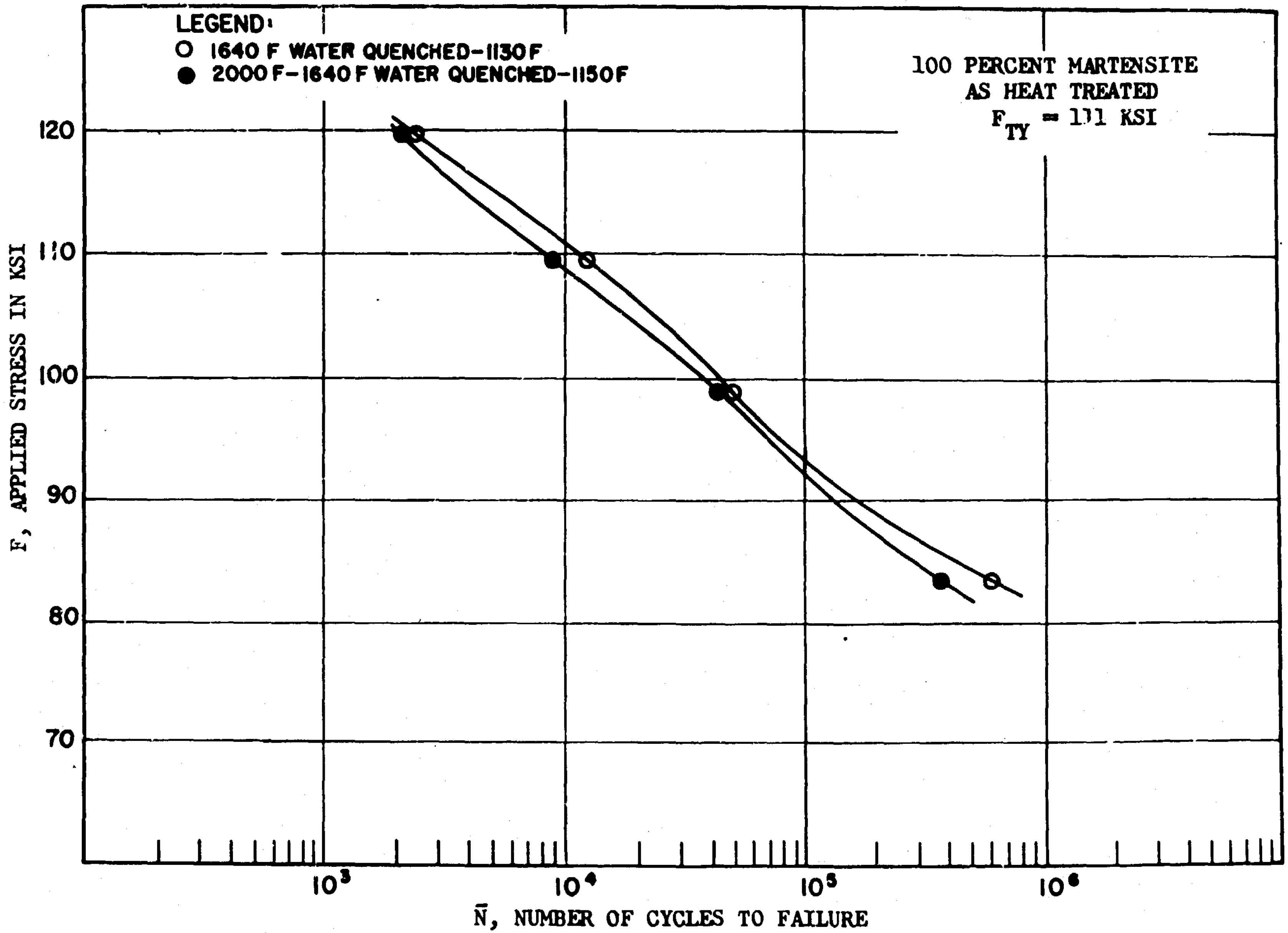

Figure 14 - Effects of Austenitizing Treatment on the Relationship between Applied Stress and Log Number of Cycles to Failure for an HY-80 Composition Heat Treated to 111,000-PSI Tensile Yield Strength

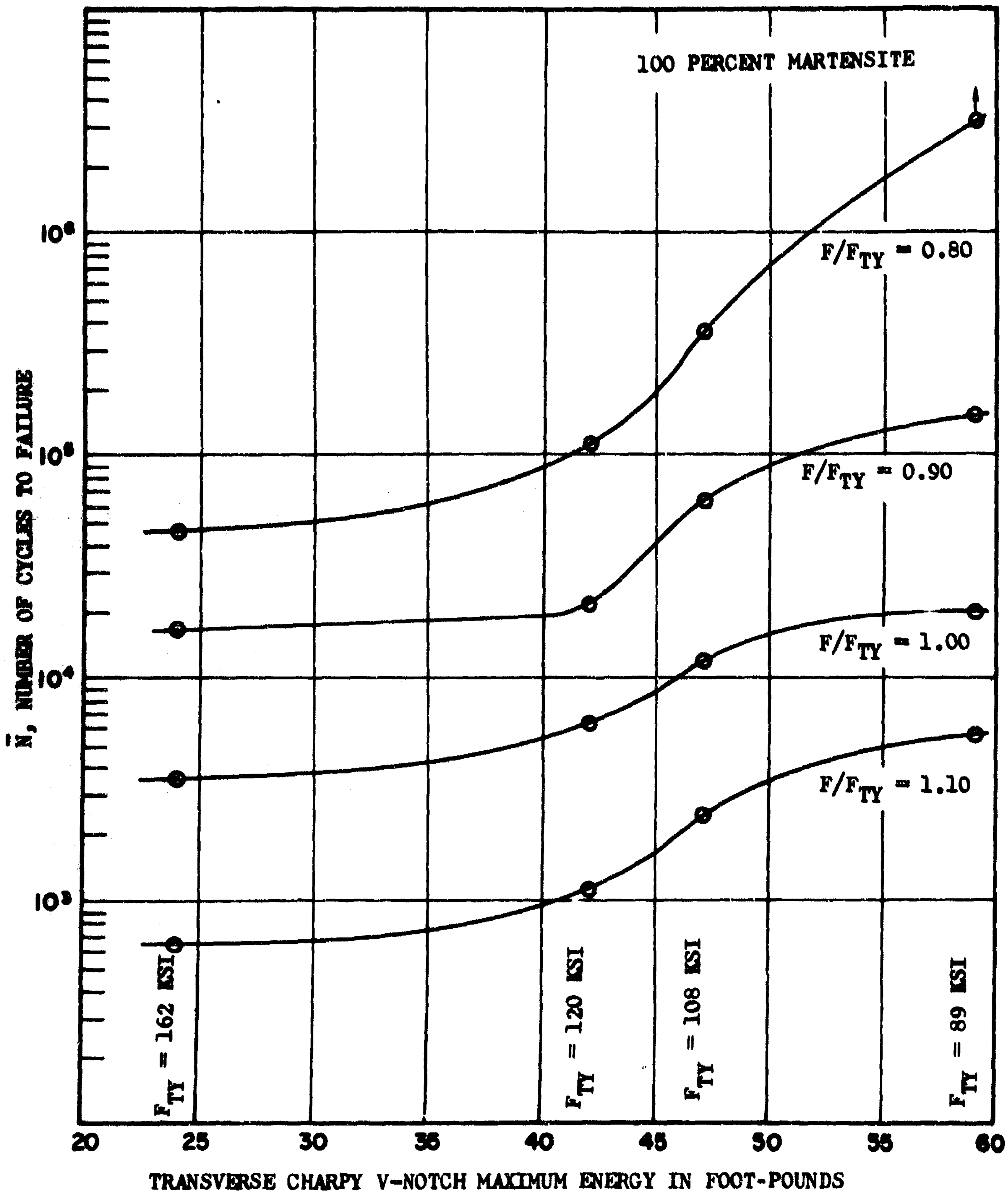

Figure 15 - Transverse Charpy V-Notch Maximum Energy versus Log Number of Cycles to Failure for an As-Heat-Treated HY-80 Composition at Four Ratios of Applied Stress to Tensile Yield Strength

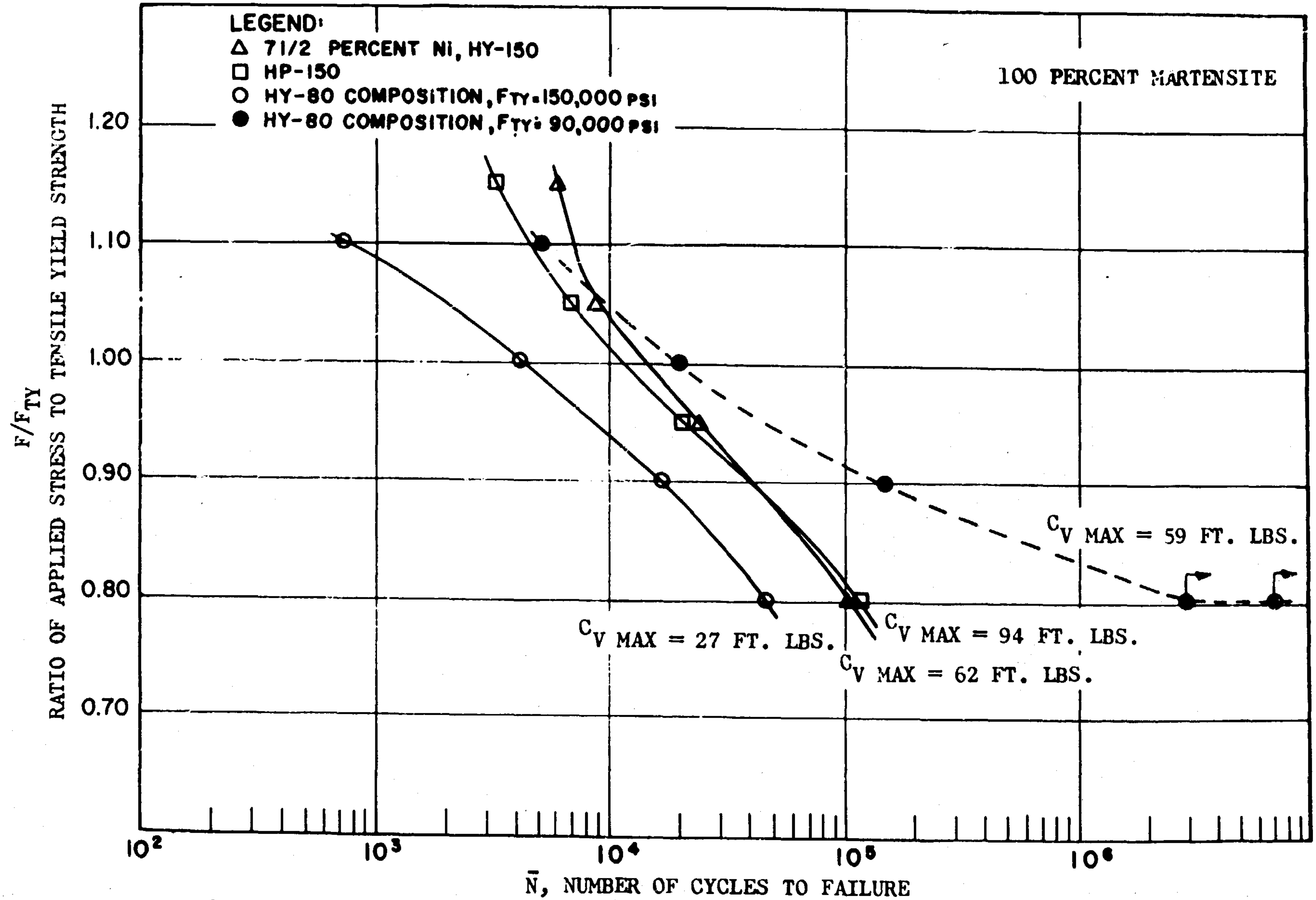

Figure 16 - Comparison of the Fatigue Properties of an HY-80 Steel and Experimental Steels Heat Treated to 150-KSI Yield Strength